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Energy-saving operation and optimization of thermal comfort in thermal radiative cooling/heating system

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Abstract

The energy-saving operation in the thermal radiative cooling/heating system has been verified. The coefficient of performance (COP) has been experimentally evaluated by changing the water temperature and the flow rate to control the heat amount. The energy-saving operation has been achieved by increasing the flow rate for the same heat amount. The thermal comfort has also been evaluated by calculating the predicted mean vote (PMV). In the case of the energy-saving operation, it is expected that the heat amount by radiation is reduced and impair the thermal comfort. However, it is found that its reduction has a small effect on the thermal comfort.

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Keywords: energy-saving; thermal comfort; heat pump; thermal radiative cooling/heating system

1. Introduction

In the recent year, energy consumption around the world has been continuously increasing and the problems of global warming and depletion of fossil fuel has been a major concern. Therefore, the introduction of renewable energy such as solar and wind power generation and energy-saving measures have attracted a great deal of interest. As energy-saving measures in the demand side, the cooling and heating systems have been focused, because they account for one quarter of the energy consumption in the residential sector in Japan [1]. The thermal radiation type heating and cooling systems have been studied for the concern about energy conservation and energy management

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in buildings [2-5]. Therefore, the thermal radiative cooling/heating system which has an active use of radiative heat transfer and heat pump technology for the thermal energy supply has been investigated in our research by evaluating the performance of the energy efficiency, thermal radiation and thermal comfort [6-9]. This system has been expected to be available to power control in the demand side such as demand response during tight supply, because this system has the heat exchange and transfer by using water as a medium and it is controllable load equipment such as air conditioners and heat pump water heater [10, 11]. Then, the heat transfer mechanisms and the operation for efficient heating and cooling have been studied in detail in order to accommodate a variety of power control.

In this research, in order to verify the energy-saving operation in the thermal radiative cooling/heating system, the coefficient of performance (COP) in cooling and heating have been evaluated experimentally when the radiation amount is controlled by changing water temperature and the flow rate. The thermal comfort has also been evaluated in these case by estimation of predicted mean vote (PMV) based on the heat radiation model.

2. Experiment outlines

2.1. Thermal radiative cooling/heating system characteristics

The proposed thermal radiative cooling/heating system used in this work is composed of the indoor units of heat sinking radiators and the outdoor unit which contains the heat pump and the heat exchanger. Figure 1 shows the block diagram of the proposed system. In the case of heating, the heat is absorbed from the atmosphere by the heat pump. Hot water is produced by transferring the heat in the heat exchanger. The room is warmed by circulating the hot water inside the radiator. For transferring the heat in the room, the heat transfer by radiation has been actively utilized. On the other hand, in the case of cooling, which is the reverse process of heating, cold water is produced in the heat exchanger by releasing heat into the atmosphere using the heat pump. The circulation of the cold water into the radiator brings a cooling effect in the room. Moreover, a ceramic material coating with high emissivity in far-infrared region applied to the room walls, ceiling and the surface of the radiators. This coating is expected to increase the radiant heat transfer effect. The characteristics of the thermal radiative cooling/heating system are indicated as follows: It is comfortable because there is no feeling of air flow which is usually caused by warm or cold air. In addition to that, the temperature variations in the room are small. Also, it is safer for health because it prevents dust whirling up in the room. There is no mechanical noise other than water circulation in the radiator. Dehumidification effect can be expected during cooling process. Thus, this system can provide comfortable and healthy living environments.

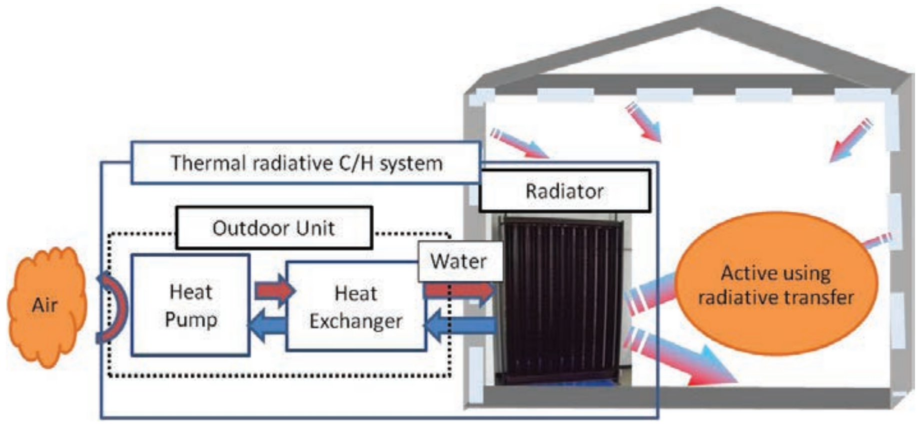

Fig. 1. Block diagram of the thermal radiative cooling/heating system.

2.2. Experimental installations

The thermal radiative cooling/heating system used in the experiments of our research is installed in a room (about 50 m^2 area and 2.6 m height) on the fourth floor of a four-stories building in Tobata campus of Kyushu Institute of Technology. Figure 2 shows the layout of the room. The system has two radiators with different materials and shapes. One is made of aluminum (named as Radiator A), and the other is made of steel (named as Radiator B). The shape of each radiator is shown by the photographs in Fig. 3. The temperature of the flowing water through these two radiators is controlled by a single exterior unit. In addition, it is possible to vary the water flow rate through the radiator by the ball valves attached at the inlet of each radiator. However, the flow rate in one radiator decreases with increasing of the flow rate in the other radiator due to the pipes structure. Therefore, in this work, only Radiator A is using for the research in order to evaluate in detail the characteristics by closing the valve of the Radiator B.

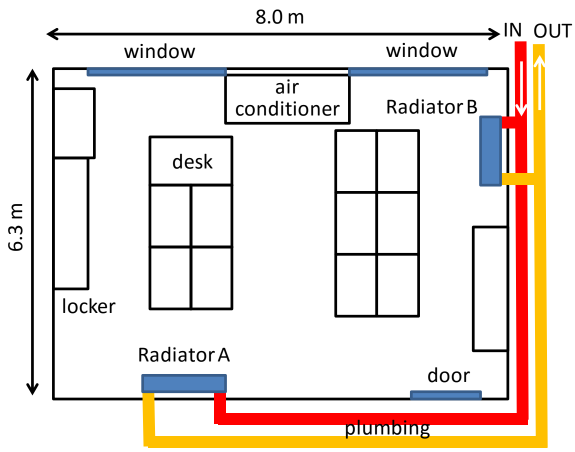

Fig. 2. Layout of the experiment room.

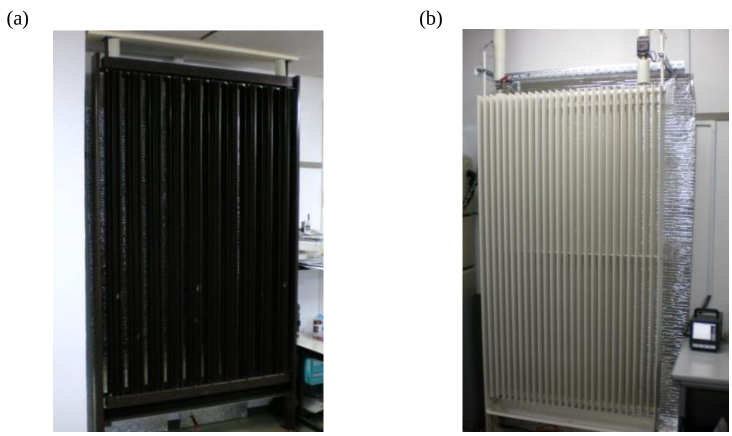

Fig. 3. Photographs of (a) Radiator A made of aluminum, and (b) Radiator B made of steel.

2.3. Energy-saving operation by changing water temperature and the flow rate

In this system, room temperature is usually adjusted by setting the input water temperature flowing through the radiator. That is, the heat amount from the radiator is controlled by changing the input water temperature into the radiator, since it is considered to be approximately proportional to the difference in water temperature and room temperature. For example, during heating, it is possible to obtain about 2.4 times the heat amount by changing the water temperature from 35 to 55 ºC [9]. However, the heat amount can be also controlled by varying the water flow rate [8]. Therefore, the heat radiation performance of the radiator was evaluated by measuring the heat amount with respect to the change of water temperature and flow rate. The heat amount Q [W] from the radiator is estimated by measuring water flow rate L [L/min] and water temperature difference $\varDelta T$ [K] between the inlet and the outlet of the radiator and given by the following equation,

$$Q = C_p \times \rho \times L \times \Delta T \times \frac{1000}{60}. \tag{1}$$

Here, C_p and ρ is the specific heat capacity and the density of water, respectively. The values of them are using 4.18 kJ/kg·K and 1.00 kg/L. Then, the COP is calculated by dividing the estimated heat amount Q [W] from the radiator by the measured power consumption P [W] of the system. The energy-saving operation is verified by comparing the COP under the condition where the heat amount is kept constant by adjusting the water temperature and the flow rate.

2.4. Evaluation of the thermal comfort

The thermal comfort is verified in the case of the energy-saving operation by changing the water temperature and the flow rate. The index of comfort uses PMV. PMV is an index that predicts the mean value of the thermal sensation votes of a large group of persons on a sensation scale expressed from -3 to +3 corresponding to the categories "cold," "cool," "slightly cool," "neutral," "slight warm," "warm" and "hot," as shown Fig. 4. The value of PMV is calculated by the theoretical expression based on the human body heat load taking into account the thermal six elements, which are temperature, humidity, air flow, mean radiant temperature (MRT), metabolic rate and amount of clothing.

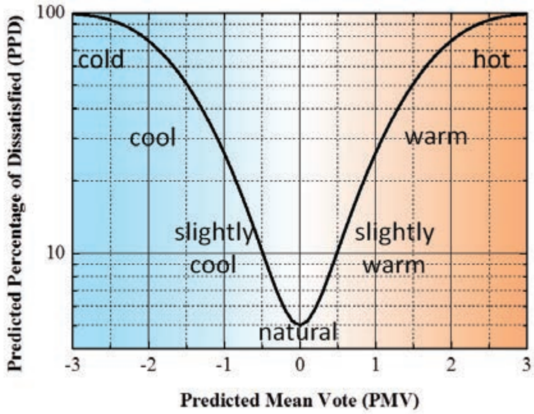

Fig. 4. Relationship between the predicted mean vote (PMV) and the percentage of dissatisfied (PPD).

In the case that the thermal comfort is verified by comparing PMV, it is assumed that the other five elements are constant, only MRT is changed, because the heat amount is kept constant by adjusting the water temperature and the flow rate. The values of these five elements are using the standard value. It is calculated the MRT at a position of 120 cm away from the radiator. In this calculation of MRT, it is assumed that the radiator temperature is the same as the water temperature and the temperatures of the walls, floor and ceiling are the same as room temperature. Solid angle of the radiator is also considered.

3. Experiment results

3.1. Energy-saving operation by changing water temperature and the flow rate

The experiments of the energy-saving operation are performed by adjusting the water temperature and the flow rate. In order to keep the radiation amount constant, it is necessary to reduce the flow rate as the setting of water temperature is increased in the case of heating. Figure 5(a) shows the COP in the case of changing the setting of water temperature and the flow rate under the condition of the constant heat amount of 1.9 kW in heating. It is found that the COP is good for the low setting of water temperature and the high flow rate. In this case, the returning water temperature to the heat exchanger varies corresponding to the setting of water temperature. On the other hand, in cooling, COP is good for the high setting of the water temperature and the high flow rate under the condition of the heat amount of 1.1 kW, as shown in Fig. 5(b). Thus, the energy-saving operation is possible by the low setting of water temperature in heating and by the high setting in cooling. At this time, it may impair the thermal comfort because the influence of the radiation heat transfer is reduced.

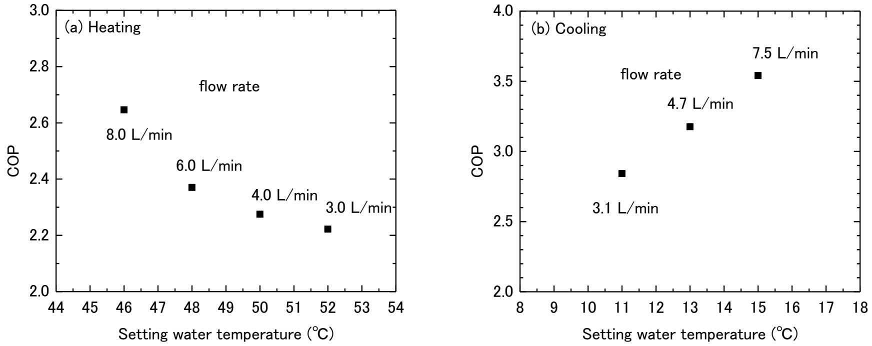

Fig. 5. COP by changing the setting water temperature and the flow rate to keep the heat amount (a) in heating and (b) cooling.

3.2. Evaluation of the thermal comfort

Tables 1 and 2 show the calculation results of MRT and PMV in heating and cooling, respectively. In these calculations of PMV, it is using room temperature of 23°C, humidity of 30%, air flow of 0.1 m/s, metabolic rate of 1.1 met and amount of clothing of 1.0 clo in the case of heating. The values are the standard values of the season, and the values of temperature, humidity and air flow are the approximate values at the time of the experiments. Water temperature (T_{water}) in the table represents the average water temperature of the radiator. In the case of cooling, room temperature of 26°C, humidity of 30%, air flow of 0.1 m/s, metabolic rate of 1.1 met and amount of clothing of 0.6 clo are used. Case D and Case H are assumed the cases of non radiation transfer from the radiator. By comparing to case C and case D, it is found that the heating effect is sufficiently obtained by the radiation. Next, it is discussed in the cases of changing the flow rate. Because the heat amount is required a constant value in order to keep the room temperature, the water temperature is varied by changing the water flow rate. Therefore, MRT is decreased in heating and increased in cooling when the water flow rate is increased. However, The PMV is a small change enough to keep the thermal category. On the other hand, the COP has been greatly improved at this time. Thus, when the heat amount is adjusted by changing the water temperature and flow rate, there is the competitive relationship between COP and PMV. In this case, it is better to set a large flow rate with priority of the COP.

Table 1. Calculation results of the MRT, PMV by changing the water flow rate in heating.

	Case A	Case B	Case C	Case D
L [L/min]	3	6	8	-
T_{water}[ºC]	47.5	45.7	44.3	23
MRT [ºC]	25.8	25.6	25.4	23
PMV	0.333	0.309	0.285	0.006

T_{room} : 23°C.
Humidity: 30%.
Air flow : 0.1 m/s.
Metabolic rate : 1.1 met.
Amount of clothing 1.0 clo.

Table 2. Calculation results of the MRT, PMV by changing the water flow rate in cooling.

	Case E	Case F	Case G	Case H
L [L/min]	3.1	4.7	7.5	-
T_{water}[ºC]	13.5	14.5	16.0	26
MRT [ºC]	24.8	24.9	25.0	26
PMV	0.035	0.046	0.066	0.215

T_{room} : 26°C.
Humidity: 30%.
Air flow : 0.1 m/s.
Metabolic rate : 1.1 met.
Amount of clothing 0.6 clo.

4. Summary

In this research, an efficient operation in the thermal radiative cooling/heating system has been investigated by measuring the heat amount controlled by water temperature and the flow rate. This energy-saving operation has been achieved by increasing the flow rate. At this time, the heat amount is maintained at a constant amount by lowering the water temperature in the case of heating and by rising the water temperature in the case of cooling. In this case, it is expected that the heat amount by radiation is reduced. However, it is found that its reduction has a small effect on thermal comfort by calculating PMV.

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